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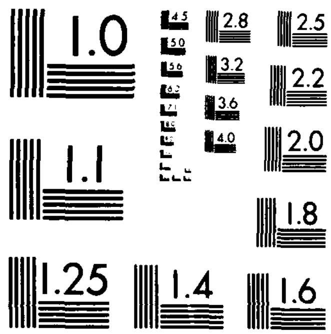
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# USE OF DEPLETION EDGE TRANSLATION FOR HIGH-SPEED MODULATION AND SWITCHING OF LIGHTWAVES

by


L. A. Coldren, J. G. Mendoza, T. R. Hausken, K. W. Lee, R. J. Simes, and R. H. Yan

University of California, Santa Barbara, CA 93106



AFOSR #85-0323 INTERIM REPORT 3/1/87-2/29/88





DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

UNIVERSITY OF CALIFORNIA SANTA BARBARA, CALIFORNIA 9310

AFOSR-TR- 88-0612

USE OF DEPLETION EDGE TRANSLATION FOR HIGH-SPEED MODULATION AND SWITCHING OF LIGHTWAVES

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The main objective continues to be the achievement of large index shifts at low voltages for applications in modulators and switches for optical processing, the device area of application has shifted from the in-plane guided wave modulator vehicle to a surface-normal modulator configuration more appropriate for spatial light modulator arrays, optical logic gates and reconfigurable optical interconnection. However, in the course of building up the surface-normal effort in the early portion of this reporting period, we also were wrapping up some important in-plane results. Thus, since these results were not previously reported, they are briefly summarized here.


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## I. Table of Contents

## II. Summary

This report covers the period from 1 March 1987 to 29 February 1988. As stated in the last interim report, the project has changed its focus somewhat since the beginning of the project. Although the main objective continues to be the achievement of large index shifts at low voltages for applications in modulators and switches for optical processing, the device area of application has shifted from the in-plane guided wave modulator vehicle to a surface-normal modulator configuration more appropriate for spatial light modulator arrays, optical logic gates and reconfigurable optical interconnection. However, in the course of building up the surface-normal effort in the early portion of this reporting period, we also were wrapping up some important in-plane results. Thus, since these results were not previously reported, they are briefly summarized here. The key new in-plane result is that the phase modulation efficiency can be enhanced by about a factor of two by placing the reverse biased pn junction near the peak of the optical mode intensity in the center of the waveguide. Experimentally we have obtained about 100°/Vmm using this new configuration as compared to our previous record result of 66°/Vmm.

The bulk of this report is concerned with a new surface-normal Fabry-Perot electro-optic modulator that is formed with a single MBE growth. Two quarter-wave AlAs/AlGaAs dielectric mirror stacks separated by a GaAs/AlGaAs MQW cavity region form the Fabry-Perot resonator structure. By doping the bottom mirror n-type and the top mirror p-type, a large electric field can be applied across the MQW spacer region with a reverse bias. With such a field the index in the cavity is varied and the resonator modes tuned. Thus, for wavelengths close to these modes the net reflectivity of the resonator is changed, providing an electrically switchable mirror. Initial experimental results have demonstrated a 2 : 1 on : off ratio. This configuration is particularly interesting because it can also be optically switched, the location of the resonances can be tuned electrically to track any temperature or wavelength drift, and one can choose to operate on either side of the resonance lines to invert the contrast.

## III. Objectives

The general objective of this work is to develop improved components for optical computing, optical interconnection and OEICs by using carrier and field effects to maximize electro-optic and opto-optic interactions. To this end more specific objectives are to experimentally and theoretically investigate novel surface-normal modulators and lasers using Fabry-Perot cavities and MQW active regions grown by MBE. Further objectives not addressed in this interim report are to investigate new active region configurations such as modulation doped MQWs and quantum-wire layers.

## IV. Progress

1. Wrap-up of in-plane results funded by AFOSR

During this reporting period many important results from work initiated earlier were achieved. The key accomplishment was stimulated from a complete theoretical analysis of the waveguided depletion-edge-translation (DET) configuration that was completed[1]. Whereas previous work considered only the placement of the pn junction at the top of the waveguide layer so that the active region was all n-type, the theory indicated that by placing the pn junction near the center of the waveguide, where the optical intensity is highest, the net phase shifting efficiency would be maximized. Furthermore, the effect continued to increase with increased doping, unlike the case with the junction at the edge where $n \approx 10^{17}$ $cm^{-3}$ is the optimum. Figure 1 gives the theoretical results for the new configuration along with initial data taken from a device with slightly different parameters[1,2]. As before, two field and two carrier effects are important. However, with the junction at the center the linear electro-optic (LEO) effect and the electrorefraction (ER) effects nearly triple, and the contribution of bandfilling (BF) and the free carrier plasma (PL) increase by a little less than a factor of two. The experimental results[3] (TE $\Rightarrow$ 100°/Vmm) represent the highest modulation efficiency ever reported in a simple double-heterostructure waveguide.

As mentioned above the in-plane waveguide application of our DET concept is no longer supported by AFOSR. It does continue, however, under another sponsor. In recent months MQW active regions have been evaluated with the expected improvement in the ER effect. Waveguides formed by impurity-induced-disordering have also been shown to be useful[4]. Most recently, encouraging results have been obtained for waveguide crossing switches using reverse biased DET pn junctions.

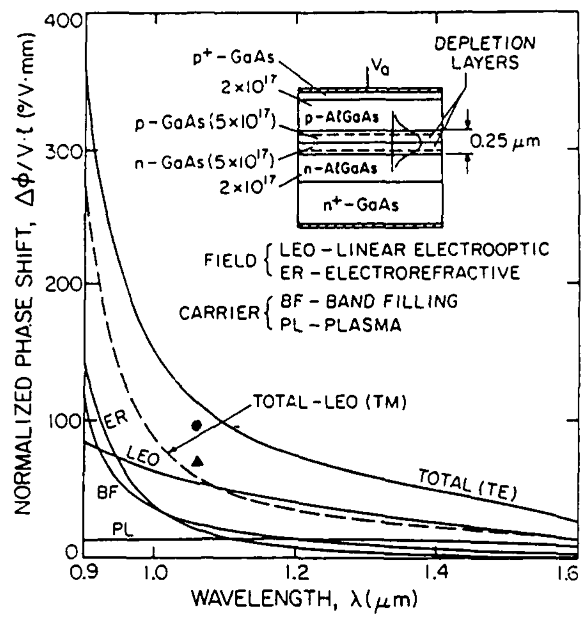


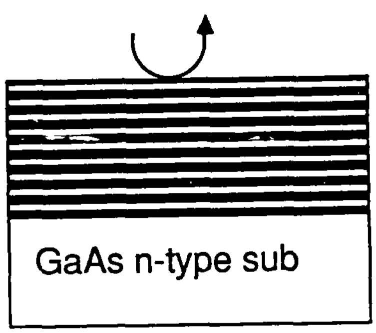

Figure 1. Theoretical values of normalized phase shift versus wavelength for the P/p/n/N configuration shown in the inset.

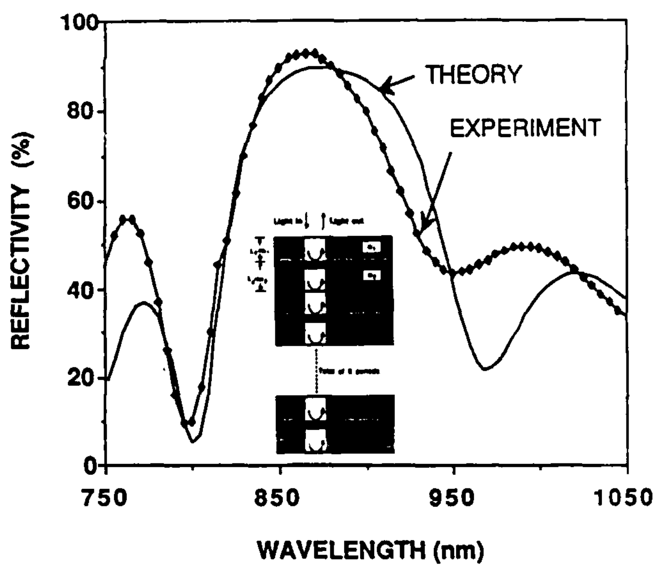
## 2. Surface-Normal Fabry-Perot Multi-Quantum Well Index Modulator

Semiconductor optical modulators that operate on light normal to the plane of the device rather than in a waveguide configuration are of considerable interest because of their potential applications in optical computing or for optical interconnects. Surface normal devices that are controlled by electrical [5-7] or optical [8] inputs have been the subject of recent work. In this report, we give the first report of an electrically-tunable Fabry-Perot (FP) index modulator. The modulator consists of two quarter-wavelength stacks separated by a MQW spacer region across which an electric field can be applied. The optical tunability of such a structure has been demonstrated [8], but there has been no implementation of electrical tunability [7,9]. In our case, the electric field shifts the FP modes to yield efficient amplitude modulation for wavelengths near the resonances. With our initial devices, we find that on:off contrasts of approximately 2:1 are possible with relatively low applied voltages (~25 - 30 V) and fields (~125 kV/cm). Generally, we prefer index modulation as opposed to absorption modulation, because absorption may cause heating in large arrays and because index modulation makes it possible to switch light from one place to another. This configuration is particularly interesting because it can also be

optically switched, the location of the resonances can be tuned electrically to track any temperature or wavelength drift, and one can choose to operate on either side of the resonance lines to invert the contrast.

The FP structure was designed [10-12] to operate in the reflection mode at 0.9 μm, sufficiently close to the absorption edge that the quadratic electro-optic in the MQW region was large, but sufficiently far away that the associated absorption loss was small. The entire structure was grown by molecular beam epitaxy (MBE) in a Varian Gen II. As mentioned above, the mirrors consisted of quarter-wave stacks as shown schematically in Fig. 2a. Figure 2b plots the theoretical and experimental reflection versus wavelength of a single eight-period grating mirror. The experimental curve is somewhat distorted by the use of an aluminum mirror as a reference. Thus, the actual agreement between theory and experiment is better than indicated. For the theory an exact transmission matrix multiplication approach was used. In this approach loss or gain can be included in each layer.



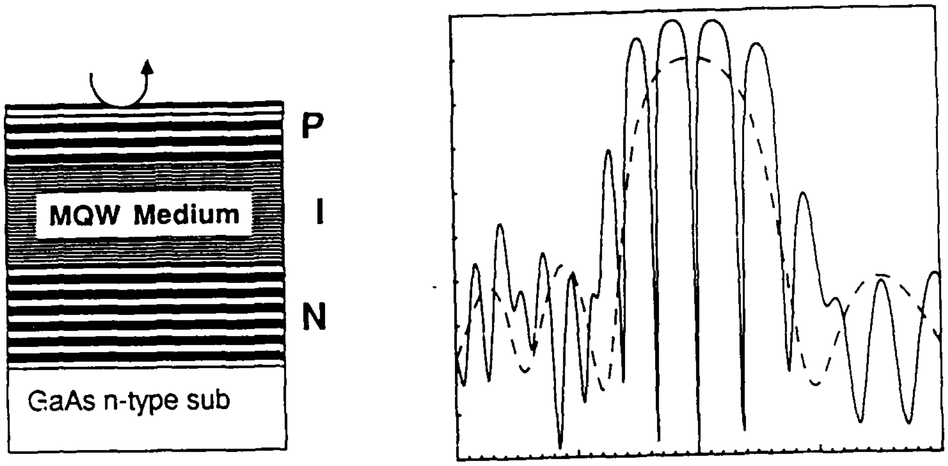




(a) (b)

Figure 2. (a) Schematic of grating mirror. (b) Reflection vs. wavelength for eight periods of $AlAs/Al_{.2}Ga_{.8}As$ grown on GaAs.

Figure 3 gives a schematic and theoretical response of a Fabry-Perot structure with a 103 period MQW region separating the gratings. Figure 4 is an SEM cross-section of the experimental MBE-grown structure. The mirrors of the étalon were designed so that their

net reflectivities would be equal, and they were doped to ~1 x $10^{18}$ $cm^{-3}$ as shown in Figure 4. The MQW spacer was not doped.




(a) (b)

Figure 3. Fabry-Perot (a) structure and (b) theoretical response. 103- 100Å GaAs quantum-wells separated by 100Å $Al_{.2}Ga_{.8}As$ barriers are assumed to separate the grating mirrors. Top mirror has five periods and bottom mirror has 8.5 periods.

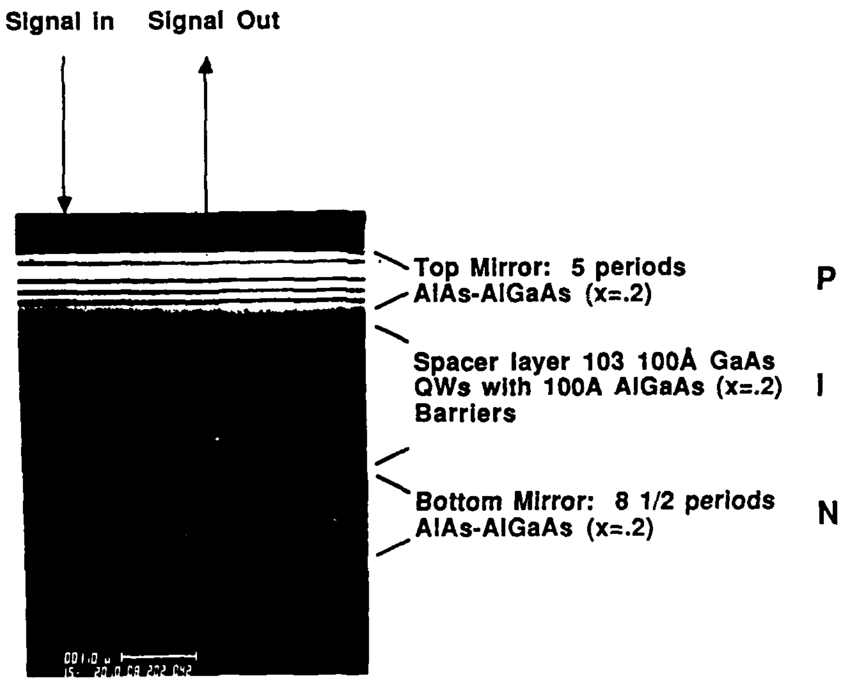



Figure 4. SEM cross-section of FP structure as grown by MBE. The mirrors are quarter-wavelength thick stacks of AlAs (756Å) and $Ga_{.8}Al_{.2}As$ (650Å). The AlAs layers appear as dark stripes; they were delineated by etching the sample for 3 seconds in 20:1 $H_20$:HF.

A reflection spectrum of the as-grown material is shown in Figure 5. Ideally, the minima should go to zero; however, with loss in the spacer region and a non-uniform layer thickness across the measurement area, non-zero minima would be predicted. On other samples, we have measured minima as low as 15%. It should be possible to improve this result by using a smaller probe area and by choosing the reflectivity of the top mirror, $R_1$, to be: $R_1 = R_2 \exp(-2\alpha L)$, where L is the spacer layer thickness and $\alpha$ is the incremental loss in the MQW spacer.

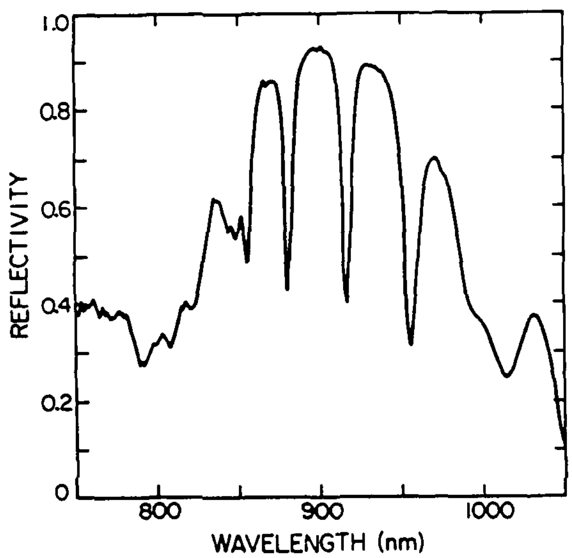
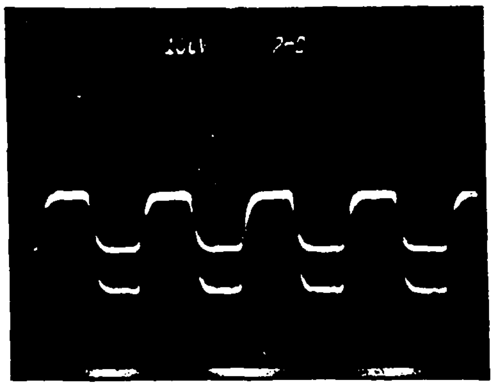



Figure 5. Measured reflection spectrum of as-grown material. There are several FP resonances within the broad-band reflection of the dielectric grating mirrors in good quantitative agreement with theory.

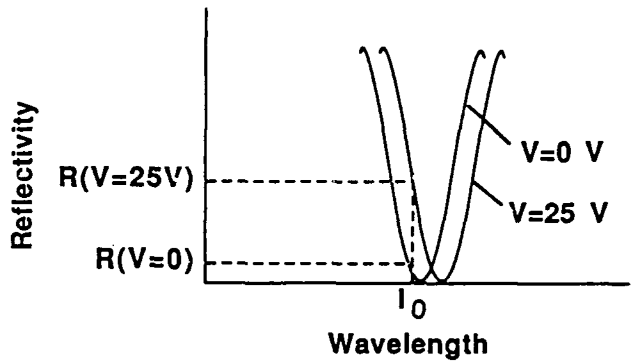
Devices were formed by cleaving squares (area ~0.25 $mm^2$) after ohmic contacts had been formed. For testing monochromatic light (from a 0.25m monochromator) was focused at an angle of incidence of ~20° onto an unmetallized area of the top surface of a device, and the reflected signal was monitored. The devices were operated only with a reverse bias, and the power dissipation was kept low (<100μW) to prevent any undesirable thermal effects. All measurements were made at room temperature.

We measured the contrast ratio of our device at several wavelengths tuned to be close to three resonances of the étalon, approaching the absorption edge of the MQW spacer. The applied bias was switched from 0 V to 25 V, changing the field across the MQW spacer from 0 V/cm to 125 kV/cm assuming the voltage is uniformly dropped across the

MQW spacer. At 913 nm and 880 nm , we measured contrast ratios of 1.1:1 and 1.8:1, respectively. Figure 6a is a scope trace demonstrating device operation at 880 nm. The schematic in Fig. 6b indicates how the index modulation that shifts the resonance wavelength is converted to reflection modulation. At 880 nm and 913 nm, we are operating the device relatively far from the excitonic absorption peak, which occurs at ~850 nm. At both of the above wavelengths, the measured contrast ratio is due to a positive change of the refractive index of the MQW spacer with electric field in the spacer layer.



(a)




(b)

Figure 6. (a) Modulation data for FP reflection modulator ($\lambda_{test}$ = 880 nm). The oscilloscope trace (horizontal axis - 2 ms/div; vertical axis - 10 $\mu$V/div) shows the intensity of the detected signal for $V_{app}$ = 0 V and $V_{app}$ = 25 V. The signal detected at Vapp = 0 V is 12 $\mu$V, and at $V_{app}$ = 25 V it is 22 $\mu$V. There is an optical chopper in the light beam operating at 250 Hz causing both signals to go to zero. (b) Schematic showing how modulation can be achieved. Applying a field across the spacer region of the Fabry-Perot leads to a change in the refractive index of the material which causes the position of the Fabry-Perot modes to shift.

To estimate the change in the index of refraction of the MQW spacer as a function of electric field, we measured the shift of the FP resonances at 890 nm. For applied biases of 35 V (1.75 x $10^5$ V/cm across the FP spacer) and 25 V (1.25 x $10^5$ V/cm), the FP resonance shifts by ~4Å and ~2Å, respectively, from which we infer refractive index changes in the spacer layer of 0.04% and 0.02%. The portion attributable to the linear-electro-optic (LEO) effect is 0.016% and 0.01%, respectively, The remaining shift varies approximately quadratically with voltage, suggesting that a quadratic-electro-optic (QEO) effect associated with a shift in the absorption edge is significant. The portion of the shift

due to the LEO and QEO effects was also verified by polarization measurements. With the light polarized along the [110], the index shifts add, while with the polarization along the [$\bar{1}$10], they subtract. At a wavelength of 882nm and a field of 125kV/cm we find that the modulation due to the QEO is four times that from the LEO.

On the same device at 860 nm, we measured a contrast ratio of ~2:1. However, at this wavelength, the change in the intensity of the reflected light is opposite to that one would expect if the refractive index change were positive. The modulation at 860 nm is due to a combined negative change in the refractive index and a change in the absorption of the material comprising the spacer. Such an effect has been previously observed [13,14] and is consistent with our theoretical understanding. Figure 7 indicates schematically what is happening when a transverse electric field is applied to a quantum-well. As indicated four effects occur. There is a shift in the energy levels of the electrons and holes, a reduction in the wavefunction overlap, and there are resulting changes in absorption and the refractive index.

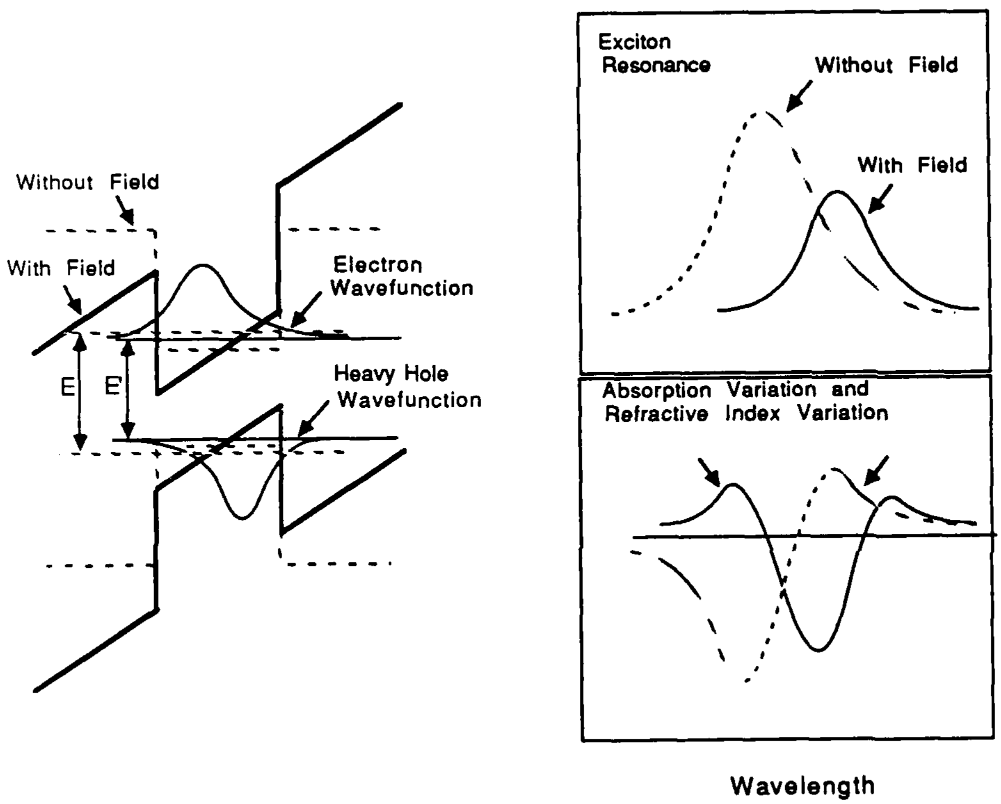



Figure 7. Modeling of excitonic effects in quantum-wells due to the external field.

near 860 nm behaved as a function of applied field. The resonance shifts and its shape changes. When the voltage was increased from 20 V to 30 V, the resonance shifted to shorter wavelength rather than continuing to move toward longer wavelength as would have been expected if the index shift was positive. The observed phenomenon can be modeled using a single exciton, approximated with a Lorentzian lineshape [15]. As indicated in Fig. 7, the exciton position is a function of electric field. Figure 8b shows the calculated results assuming exciton peaks at 850, 854 and 862 nm for applied biases of 0, 20 and 30 V, respectively. The peak absorption for each was assumed to be $5x10^3$, $3.8x10^3$ and $2.6x10^3$ $cm^{-1}$. These values are taken from reference [14] and scaled because of the reduced barrier height in our samples (x = 0.2 vs. x = 0.4). The general behavior of these curves does not depend on the exact value of position and strength, as long as the relative relations are maintained. As can be seen good qualitative agreement between theory and experiment is observed.

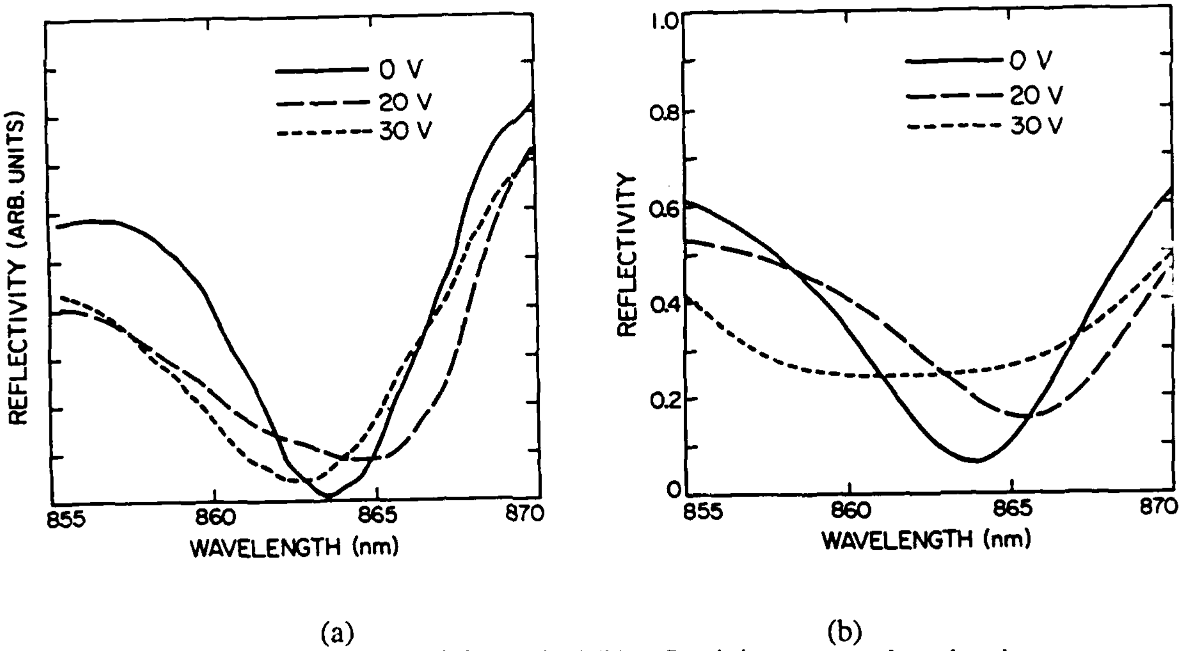



Figure 8. Experimental (a) and theoretical (b) reflectivity vs. wavelength using our model. Both index and absorption modulation are significant at 860nm.

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## V. Conference & Journal Publications

1. A. Alping, X.S. Wu, L.A. Coldren, "Wavelength Dependence of High-Performance AlGaAs/GaAs Wave-guide Phase Modulators", *Electron. Letts.*, **23**, 93-95 (January 1987).

2. L.A. Coldren, A. Alping, X.S. Wu, T.R. Hausken, "Optical Waveguide Phase-Shifters for High-Speed Signal Processing", *Conference on Optical Fiber Communication*, Reno, NV, paper TuQ34 (January 1987).

3. T.R. Hausken, K. Lee, R. Simes, R.Yan, J. Mendoza-Alvarez, N. Dagli, L.A. Coldren, "Optical Waveguide Phase Modulators in AlGaAs/GaAs with Very High Figures-of-Merit", *45th Annual Device Research Conference*, Santa Barbara, CA, paper IIIA-3 (June 1987)

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5. L.A. Coldren, J.G. Mendoza-Alvarez, R.H.Yan, "Design of Optimized High-Speed Depletion-Edge-Translation Optical Waveguide Modulators in III-V Semiconductors", *Appl. Phys. Letts.*,Vol. **51**, 792-794 (September 1987).

6. J.G. Mendoza-Alvarez, L.A. Coldren, A. Alping, R.H. Yan, T. Hausken, K. Lee, K. Pedrotti,"Analysis of Depletion Edge Translation Lightwave Modulators", *IEEE Journal of Lightwave Technology and IEEE Journal of Quantum Electronics* Joint Issue, **QE 24**, (June 1988).

7. R.J. Simes, R.H. Yan, R. Geels, L.A. Coldren, J.H. English and A.C. Gossard, "Surface-Normal Fabry-Perot Multi-Quantum Well Index Modulator", *Conference on Lasers and Electro-Optics*, Anaheim, CA, paper TuE2 (April 1988).

8. R.J. Simes, R.H. Yan, R.S. Geels, L.A. Coldren, J.H. English, and A.C. Gossard, "Electrically Tunable Fabry-Perot Mirror using Multi-Quantum Well Index Modulation", submitted to *Appl. Phys. Letts.*

## VI. Related Papers

1. R. Geels, R.H. Yan, J.W. Scott, S.W. Corzine, R.J. Simes and L.A. Coldren, "Analysis and Design of a Novel Parallel-Driven MQW-DBR Surface-Emitting Diode Laser", *Conference on Lasers and Electro-Optics*, Anaheim, CA, paper WM1 (April 1988).

## VII. Personnel

1. Professor Larry A. Coldren, PhD: Principal Investigator.
Dr. Coldren received his doctorate from Stanford University in 1972. He spent the next twelve years at Bell Labs before moving to the University of California at Santa Barbara in 1984. He holds 21 patents in the areas of surface-acoustic-wave signal processing devices, microfabrication processes and III-V compound optoelectronic devices for optical communication and processing. He has over 140 journal publications in these same areas. His current interests are in the areas of optical communication, optical computing and microfabrication technology. In this project Dr. Coldren contributed the basic ideas and research management.

2. Julio Alvarez-Mendoza, PhD: Visiting research engineer.
Dr. Mendoza received his doctorate from the University of Campinas in Sao Paulo, Brazil, 1979. He was with UCSB from 9/86 - 8/87 as a visiting associate research engineer and is currently a Titular Professor at the Research Center of the IPN in Mexico City. Dr. Mendoza was resonsible for leading and training the students and modeling and optimizing the D.E.T. modulator. He was employed during the first half of this reporting period.

3. Mr. T.R. Hausken: Research Assistant.
Mr. Hausken received his B.S.E.E. from Montana State University in 1979. He spent the next five years at Texas Instruments first with ac plasma display development, and later with MOS memory failure analysis. He began studies at UCSB in 1/85 and was responsible for testing of optical devices.

4. Mr. K.W. Lee: Research Assistant
Mr. Lee received his B.S. degree from Massachusetts Institute of Technology in 1983.and was employed by Raytheon Research Division in Lexington, Massachusetts from 1983/86. He began his studies at UCSB at 1986 and was responsible for fabrication and testing of devices. He was employed during the first half of this reporting period.

5. Mr. R.J. Simes: Research Assistant
Mr. Simes received his B.S. in Dec. 1983 from UCSB and started graduate studies immediately thereafter. His interests and contributions include molecular beam epitaxy of the surface-normal optoelectronic structures.

6. Mr. R.H. Yan: Research Assistant
Mr. Yan received his B.S. degree from National Taiwan University in 1984. He joined UCSB in 1986. His contributions included assisting in the development of the theory to

model the D.E.T. phase modulator and design and testing of the surface normal modulator.

## VIII. New Discoveries

During this reporting period two new discoveries were made. The first was the realization that about twice the phase shift could be obtained in a phase modulation by placing the reverse biased pn junction at the peak of the optical mode intensity.

The second new result was the first demonstration of an electro-optically modulated vertical Fabry-Perot mirror. On/off ratios > 10:1 with bias < 10v are predicted by our theory.

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